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ORIGINAL ARTICLE

Efficiency of municipal solid waste management in the district municipalities of the southern macro region of Peru

Eficiencia de la gestión de residuos sólidos urbanos en los municipios distritales de la macrorregión sur del Perú

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Abstract

The central objective of this study is to analyze the level of efficiency in the management of urban solid waste in the district municipalities of the southern macroregion of Peru in the year 2022 and how it is affected by different variables and management strategies. For this, information from the National Registry of Municipalities (RENAMU) for the year 2022 prepared by the INEI was used. The hypothetical-deductive method was used with a quantitative approach through an envelopment analysis model that allowed estimating the level of efficiency of the 174 urban district municipalities. Subsequently, a Tobit model was estimated to find how the management instruments affect the level of efficiency of the municipalities. It is concluded that some districts operate with high efficiency in solid waste management, such as Machupicchu, Pichari, Juli, while others have room to use their resources efficiently, such as Potoni, Cabanillas and Quilcapuncu. Furthermore, it was found that municipalities with greater efficiency manage to collect a greater amount of solid waste per capita and a higher level of waste collection coverage with similar resources to those inefficient municipalities. On the other hand, the implementation of waste management plans, urban development plans and institutional strategies are positively and significantly related to the level of efficiency.

Keywords: data envelopment analysis, efficiency, solid waste management, Tobit model.

Thematic classification: Q53: Air pollution, water pollution, noise pollution, hazardous waste, solid waste, recycling. H11: Structure, scope, and performance of government.

Resumen

El objetivo central de este estudio es analizar el nivel de eficiencia en la gestión de residuos sólidos urbanos en los municipios distritales de la macrorregión sur del Perú en el año 2022 y cómo se ve afectada por diferentes variables y estrategias de gestión. Para ello, se utilizó información del Registro Nacional de Municipalidades (RENAMU) del año 2022 elaborada por el INEI. Se empleó el método hipotético-deductivo con un enfoque cuantitativo mediante un modelo de análisis envolvente que permitió estimar el nivel de eficiencia de las 174 municipalidades distritales urbanas. Posteriormente, se estimó un modelo Tobit para encontrar cómo afectan los instrumentos de gestión al nivel de eficiencia de las municipalidades. Se concluye que algunos distritos operan con alta eficiencia en la gestión de residuos sólidos, como es el caso de Machupicchu, Pichari, Juli, mientras que otras tienen margen para utilizar sus recursos de manera eficiente, como Potoni, Cabanillas y Quilcapuncu. Además, se encontró que las municipalidades con mayor eficiencia logran recolectar una mayor cantidad de residuos sólidos per cápita y un mayor nivel de cobertura de recojo de residuos con recursos similares a aquellas municipalidades ineficientes. Por otro lado, la implementación de planes de gestión de residuos, planes de desarrollo urbano y estratégicos institucionales se relacionan positiva y significativamente con el nivel de eficiencia.

Palabras clave: análisis envolvente de datos, eficiencia, gestión de residuos sólidos, modelo Tobit.

1. Introduction

The rapid population growth in urban environments poses a significant challenge for the proper management of generated solid waste. In line with Sustainable Development Goal 11, which focuses on "Sustainable Cities and Communities", the need for efficient solid waste management is highlighted. This effective management becomes essential to ensure that people in these urban environments can enjoy a decent and healthy life (School of Public Management of the Universidad del Pacífico, 2021). Currently, the efficient management of urban solid waste in the southern macroregion of Peru, which comprises the regions of Arequipa, Apurímac, Cusco, Moquegua, Puno, and Tacna, is crucial, where population growth and economic development have triggered a notable increase in waste generation, which has generated a problem that demands immediate and strategic attention.

The southern regions of Peru comprise 16% of the gross domestic product and 16% of the total population of Peru with 5,342,472 people (National Institute of Statistics and Informatics [INEI], 2022). In addition, according to the Ministry of the Environment [MINAM] (2021), between 2014 and 2021, at the national level, the average daily production of municipal solid waste has increased from 19 thousand to 21 thousand tons. Also, in 2011, the Andean region had a solid waste generation per capita of 0.547 kilograms per inhabitant per day, while the coast registered 0.628 kilograms. On the other hand, the municipal solid waste disposed of in landfills or sanitary landfills was approximately 9 million tons (Ministry of the Environment [MINAM], 2014).

Solid waste refers to materials in a solid or semi-solid state that must be disposed of by the generator due to national regulations or the risks they pose to health and the environment. Its management is the responsibility of the provincial and district municipalities, which must also implement management instruments, such as the comprehensive environmental management plan for solid waste (PIGARS). This plan addresses all stages of waste management and technical, environmental, economic, institutional, and legal aspects. It also aims to solve environmental problems caused by urban waste, minimizing its impact on the aquatic environment and sanitation systems, prioritizing environmental protection and public health (Rondón et al., 2016).

In line with the above, data provided by the Comptroller General of the Republic of Peru (2019) reveals that, up to 2019, 36% of municipalities lacked a solid waste characterization study. Similarly, of the 45% of district municipalities that had this study, 79% did not maintain coordination with the provincial municipalities. In addition, only 21% of them had a comprehensive environmental management plan for solid waste (PIGARS). These figures show the lack of a clear coordination process in terms of management instruments, which could have a negative impact on the efficiency of the service.

In this sense, it is essential to achieve efficient municipal solid waste management that integrates all social actors in an articulated manner and minimizes costs, ensuring optimal resource use. Otherwise, the social costs of assuming this responsibility will involve an increase in diseases and the creation of areas with precarious living conditions. Additionally, municipal authorities play a crucial role in fostering the growth of healthy and competitive cities, which favors attracting investments (Gómez and Flores, 2014).

Another important aspect to consider is technical efficiency, which addresses the generation of products (outputs) in terms of their quantity or quality in relation to the amount of resources or inputs (inputs) used in the production process. In general terms, efficiency is achieved by using a smaller amount of inputs for production or by producing more using the same amount of inputs (Cordeiro et al., 2012).

2. Theoretical framework

As Law 27314 states, the purpose of solid waste management in the country is to achieve its complete and sustainable management, through the coordination, unification, and adaptation of policies, plans, programs, strategies, and actions of those involved in its management and handling, applying the policy principles defined in Article 3 of the aforementioned law. Likewise, said law, in its article 10, indicates that it is the responsibility of the district municipalities to provide the collection and transportation services for the solid waste mentioned in the previous article, as well as to be responsible for the cleaning of roads, public areas, and monuments within their scope.

The composition of municipal solid waste (MSW) differs depending on the geographic location within the country and the size of the community where it is generated. This variability implies that a large urban area may generate different types and per capita quantities of waste than a smaller rural community (Jiménez, 2015). In this sense, more effective waste management is required to prevent the creation of additional impact on the atmosphere and, at the same time, protect the soil and water (Sánchez-Muñoz et al., 2020).

Numerous studies use data envelopment analysis (DEA) to create an evaluation tool that integrates various indicators into a model, with the purpose of evaluating the efficiency of solid waste management (Cavallin et al., 2016). Among this body of research, studies such as that of Orihuela (2018) stand out, which indicates that the district municipalities of Peru have a lower level of efficiency in solid waste collection management compared to the provincial municipalities. This phenomenon is mainly attributed to the lack of adequate equipment, especially machinery, such as garbage trucks, which is the main cause of their low efficiency. In this context, Betanzo et al. (2016) mentions the importance of examining the density or volumetric weight factor in waste, as this factor influences the speed at which collection trucks are filled.

Another important factor is that the cleaning staff, who are responsible for the activities related to waste management, do not always have the required training and experience to carry out their duties efficiently; likewise, there is a frequent rotation of personnel, with the incorporation of new members in each municipal administrative transition (Bernache, 2015). To overcome this obstacle, Cervantes and Castellanos (2022) and Zhou et al. (2022) suggest implementing comprehensive training programs for the cleaning personnel involved in these processes.

According to Bernache (2015), another organizational challenge is related to the lack of sufficiency in the coverage of collection and treatment services for municipal solid waste (MSW), where coverage is defined as the indicator that reflects the percentage of users served by municipal collection systems. This problem originates from the discrepancies existing in the practices adopted by the organizations responsible for MSW management, leading to inefficient waste management and presenting a significant challenge to achieving sustainable waste management.

However, these emerging challenges not only present obstacles but also open up opportunities and ways to efficiently use these wastes, changing the perspective of seeing these materials not only as worthless waste, but as valuable resources. In this sense, Rodríguez-Díaz et al. (2022) advocate for approaching municipal solid waste management from a circular economy perspective.

Based on the above, Lamichhane and Tamang (2019) and Zhou et al. (2022) argue that effective performance in municipal waste management is intrinsically linked to the implementation of effective collection methods, the use of suitable equipment, the optimization of human resources, the acquisition of appropriate vehicles for transportation, temporal efficiency in the execution of collection and meticulous planning of the corresponding routes. Likewise, Abarca-Guerrero et al. (2015) argue that it is up to the municipalities to strengthen each of these areas, which have a positive impact on the performance of the system.

In this area, Reyna et al. (2017) identify positive factors that contribute to the improvement of the management system, which would be the support of local authorities combined with the implementation of strategic and logistical plans that allow for annual monitoring and evaluation of the process. In parallel, in the European context, the objectives and goals set out in waste management plans have played a crucial role in driving significant improvements, marking a path towards more effective and sustainable practices (Carvajal et al., 2022).

However, despite these advances, García-Mondragón et al. (2023) take a critical perspective by considering that the implementation of strategic management plans and public policies acts more as a theoretical guide for integrated solid waste management (ISWM), since the evolution and production of waste often exceed the capacity of these plans, evidencing institutional deficiencies and the persistence of unresolved problems in solid waste management.

In an international context, there are also studies that address the efficiency of solid waste management, such as the study by Mohamed et al. (2017) in the state of Jengka Pahang in Malaysia, where they use the DEA model to analyze the collection frequency per week in hours and number of garbage trucks as input variables, while the output variable was the total amount of solid waste collected in kilograms, where they showed that only three of the 23 areas evaluated achieved optimal efficiency.

Another study is by Zhou et al. (2022) who use a DEA model to evaluate the efficiency of solid waste collection and disposal in 27 cities in the Yangtze River Delta region of China, with the inputs being the investment of municipalities in solid waste treatment and the number of garbage collection trucks, while the outputs were the amount of solid waste collected and treated, from which they determined that only 9 of the total cities use their resources efficiently for proper solid waste management.

Likewise, Das Mercês Costa et al. (2024) analyze the efficiency of solid waste management in 940 urban municipalities in Brazil using a DEA model, where they consider the number of cleaning personnel and garbage trucks as inputs and the amount of solid waste collected and the population served as outputs, determining that only 12.34% of the municipalities were evaluated as efficient.

Therefore, two research questions are raised: 1) What is the level of efficiency in the management of municipal solid waste in the district municipalities of the southern macroregion of Peru in 2022? and 2) How is this efficiency affected by different variables and management strategies? To this end, the data envelopment analysis model was used to find the level of efficiency of the municipalities and to see how it is affected by different variables and management strategies.

3. Materials and Methods

This research is quantitative in approach and non-experimental in design given the nature of economic sciences (Mendoza, 2014). However, it does not intend to rule out the use of logical deduction based on basic principles of economic theories, since this approach is crucial to achieve a more complete and profound understanding of social reality (Sánchez-Bayón et al., 2023).

The information source is secondary and was obtained from the National Registry of Municipalities (RENAMU) of 2022, prepared by the INEI, which allows the use of statistical data from provincial, district, and urban municipalities to create municipal metrics that are fundamental to support management at the regional and local level, facilitating planning and effective decision-making.

3.1 Data Envelopment Analysis (DEA)

For this research, the data envelopment analysis (DEA) method was chosen, designed by Charnes et al. (1978) based on the work of Farrell (1957). This approach makes it possible to obtain a relative indicator of efficiency by comparing decision-making units (DMUs) and offers the advantage of relaxing certain strong assumptions about the functional form of production. It also allows for the use of multiple inputs to obtain multiple outputs. Thus, DEA is a non-parametric method that allows us to distinguish between a set of efficient decision-making units that offer a maximum amount of outputs using a level of inputs or the minimum level of inputs necessary to maintain the level of output.

In the DEA problem formulation to determine relative efficiency indicators, fractional linear programming techniques are used. These techniques seek to maximize the efficiency of each DMU evaluated, without relying on arbitrary weights. In this approach, multiple inputs that are independent of each other are used to generate multiple outputs. Both inputs and outputs can take various forms and be expressed in different units of measurement, as long as they maintain common characteristics to be compared between DMUs.

The solution to the problem offers an efficiency ranking among the evaluated units, but this ranking can change if there are modifications in the selected units, inputs, and outputs. Achieving maximum efficiency does not imply that the best classification obtained is the maximum possible; other units could improve their performance. This means that an efficient unit uses fewer resources to obtain the same results or achieves more results using the same amount of resources (Fonseca and González, 2002). For these reasons, the district municipalities of the urban area of the southern macroregion are specifically considered.

Data envelopment analysis (DEA) is an innovative method, introduced by Charnes et al. (1978), that is used to evaluate the efficiency of decision-making units (DMUs), such as companies or public sector entities, in a non-parametric way. In essence, DEA seeks to measure the technical efficiency of a DMU by comparing the desired outputs with the inputs used. The original model proposed by CCR focused on technologies with constant returns to scale globally, but variants have since been developed to adapt to different situations (Coelli et al., 1998).

Charnes et al. (1978), Ray (2004) and Coelli et al. (1998) point out that technical efficiency is calculated as the weighted ratio between desired outputs and inputs used. In the CCR model, also known as CRS for considering constant returns to scale, the technical efficiency of a DMU is evaluated using an input-oriented fractional program. This means that the aim is to optimize the relationship between inputs and produce the maximum possible amount of outputs with those inputs.

In other words, DEA seeks to answer the question of how well an entity is using its resources to generate products or services. If an entity operates efficiently, it will be close to the envelope that defines the upper bound of efficiency. On the other hand, entities that are below this envelope could improve their efficiency by adjusting the combination of inputs and outputs.

This methodology is relevant in strategic decision-making, as it provides information on how to improve operational efficiency and make the most of available resources. In addition, DEA has evolved over time, adapting to different contexts and playing a crucial role in the management and evaluation of efficiency in various sectors such as solid waste management (Equation 1, Equation 2, Equation 3, Equation 4).

$$h_0(\mu, v) = \frac{\sum_{r=1}^{k} y_{r0}\mu_r}{\sum_{i=1}^{m} v_{ia}x_{ia}} \tag{1}$$

$$\text{s.a.} \quad \frac{\sum_{r=1}^{k} y_{rj}\mu_r}{\sum_{i=1}^{m} v_{ij}v_i} \leq 1 \tag{2}$$

$$\mu_r \geq \varepsilon \ ; \ v_i \geq \varepsilon \tag{3}$$

$$\varepsilon > 0 \tag{4}$$

Where:

h_0 : Objective function to be maximized.

y_r : Products or outputs, where $r = 1, \ 2, \ \ldots, k$

x_i : Inputs or inputs, where $i = 1, \ 2, \ \ldots, m$

j : District municipalities of the study, also $j = 1, \ 2, \ \ldots, n$

μ : Weighted weight for products.

v : Weighted weight for inputs.

The above maximization problem can be converted into two linear programming problems, the primal and the dual.

In primal linear programming, the problem is solved by minimizing the difference between efficiency and input and output slacks (Equation 5, Equation 6, Equation 7, Equation 8).

$$g_I = \theta - 1^T s^- - 1^T s^+ \tag{5}$$

$$\text{s.a.} \ \ \theta x_0 - X\lambda - s^- = 0 \tag{6}$$

$$Y\lambda - y_0 - s^+ = 0 \tag{7}$$

$$\lambda \, , \ s^+ \, , \ s^- \geq 0 \tag{8}$$

Where:

g_I: is the objective function to be minimized.
s^- : Slack variables associated with inputs.
s^+ : Slack variables associated with outputs.
x_0 : Input vector of the reference unit (efficient unit) that is used as a point of comparison.
y_0 : Output vector of the reference unit that is used as a point of comparison.
X : Matrix containing the amounts of inputs used by each DMU.
Y : Matrix containing the amounts of outputs produced by each DMU.
λ : Weight vector assigned to DMUs in relation to inputs.

While in dual linear programming, the following is sought (Equation 9, Equation 10, Equation 11, Equation 12):

$$h_I = u^T y_0 \tag{9}$$

$$\text{s.a} \ \ \ u^T Y - v^T X \leq 0 \tag{10}$$

$$v^T x_0 = 1 \quad (11)$$

$$u \, , \; v \geq \varepsilon \quad (12)$$

Each DMU solves the optimization problem of both primal and dual linear programming in order to assign the most favorable weights to its products/outputs and its inputs/inputs. In the case that the value of θ is equal to one and all slack variables are equal to zero, the DMU is defined as efficient and is incorporated into the efficiency frontier. On the other hand, if θ is less than one, it means that there is a need to reduce inputs/inputs, without altering outputs, to position itself on the efficiency frontier. Thus, DMUs adjust their inputs with the aim of improving efficiency, and keeping outputs constant.

Therefore, for the case under study, the primal and dual linear programs will be as follows (Equation 13, Equation 14, Equation 15, Equation 16, Equation 17, Equation 18, Equation 19):

Primal:

$$g_I = \theta_i - s_{1i}^- - s_{2i}^- - s_{1i}^+ - s_{2i}^+ \quad (13)$$

$$\text{s.a} \quad \theta x_0 - \lambda_{1i} x_{1i} - \lambda_{2i} x_{2i} - \lambda_{3i} x_{3i} - s_{1i}^- - s_{1i}^- = 0 \quad (14)$$

$$\lambda_{4i} y_{1i} - \lambda_{5i} x_{2i} - y_{0i} - s_{1i}^+ - s_{2i}^+ \quad (15)$$

$$\lambda_{1i}, \lambda_{2i}, \lambda_{3i}, \lambda_{4i}, \lambda_{5i}, s_{1i}^+, s_{2i}^+, s_{1i}^-, s_{2i}^- \geq 0 \quad (16)$$

Dual:

$$h_I = u_{1i} y_{1i} + u_{2i} y_{2i} \quad (17)$$

$$\text{s.a} \quad \mu_{1i} y 1i + \mu_{2i} y_{2i} - v_{1i} x_{1i} - v_{2i} x_{2i} - v_{3i} x_{3i} \leq 0 \quad (18)$$

$$u_{1i}, u_{2i}, v_{1i}, v_{2i}, v_{3i} \geq \varepsilon \quad (19)$$

Where:

Outputs:

y_{1i} : Quantity of per capita solid waste collected (kg/inhabitant) from the i-th district municipality.
y_{2i} : Solid waste collection coverage of the i-th district municipality.

Inputs:

x_{1i} : Number of operational collection trucks in the i-th district municipality.
x_{2i} : Number of cleaning personnel in the i-th district municipality.
x_{3i} : Frequency of solid waste collection in the i-th district municipality.

Weights and slacks:

λ_{1i} , λ_{2i} , λ_{3i}: Weights associated with inputs x_1, x_2, x_3 respectively of the i-th district municipality, in the primal problem.

μ_{4i} , μ_{5i}: Weights associated with outputs y_1 and y_2 respectively of the i-th district municipality, in the primal problem.

v_{1i} , v_{2i} , v_{3i}: Weights associated with inputs x_1 , x_2 , $x_3$respectively of the i-th district municipality, in the dual problem.

u_{1i} , u_{2i}: Weights associated with outputs y_1 and y_2 respectively of the i-th district municipality, in the dual problem.

3.2 Tobit Model

The Tobit model is a statistical technique used to address censoring in data. Censoring occurs when not all observations of a variable of interest are observable or completely recorded. There can be left-censoring (when observations below a certain threshold are not recorded) or right-censoring (when observations above a certain threshold are not recorded) (Greene, 2003; Wooldridge, 2010).

This model was proposed by Tobin (1958) and is particularly useful when dealing with dependent variables that are censored; that is, they have many values that are below or above a certain limit. It is estimated using the maximum likelihood method (MLE), where the likelihood function is maximized to obtain estimates of the model parameters.

The general formulation of the upper-censored Tobit model is as follows (Equation 20, Equation 21):

$$y_i^* = x_i^T \beta + u_i \tag{20}$$

$$\begin{cases} y_i^*, & si \quad y_i^* \leq \tau \\ \tau_y, & si \quad y_i^* > \tau \end{cases} \tag{21}$$

Where:

y: Censoring point of the dependent variable.

y_i^*: Latent variable that is observed for values less than or equal to the censoring point

x_i: Explanatory variables.

u_i: Error term

In the case of DEA, as indicated by Ji and Lee (2010), the predominant methodology for identifying the factors that influence efficiency disparities between decision-making units (DMUs) is the application of Tobit regression analysis. This is because efficiency scores are subject to censoring when they exceed the maximum value; therefore, the Tobit regression method uses the efficiency scores as the dependent variable that is subject to the influences of other related variables.

Therefore, the Tobit model is used to estimate the effect of the main determinants that influence the efficiency in solid waste management, which has the following form (Equation 22):

$$\theta_i = \beta_0 + \beta_1 PRS_i + \beta_2 PDUrbano + \beta_3 PEI + u_i \tag{22}$$

Where:

i: Efficiency in per capita solid waste collection and solid waste collection coverage of the i-th district municipality.

PRS_i: Number of solid waste plans in the i-th district municipality.
$PDUrbano_i$: The i-th district municipality has an urban development plan.
PEI_i: The i-th district municipality has an institutional strategic plan.

4. Results:

Table 1 shows the operationalization of variables, distinguishing between inputs and outputs.

Table 1. Operationalization of variables

Variables Inputs (inputs of the solid waste management process))		Values	Variable type
collector_trucks	Number of operational garbage collection trucks	Values between 0 and 20	Discreet
cleaning_staff	Total number of cleaning staff	Values between 0 and 309	Discreet
frequency_rrs	Frequency of solid waste (garbage) collection carried out by the municipality	1: Daily 2: Interday 3: Twice a week 4: Once a week	Ordinal
Outputs (Productos del proceso de gestión de residuos sólidos)		**Values**	**Variable type**
coverage_rrs	Coverage of the solid waste collection service in the district	1: Less than 25% 2: From 25% to 49% 3: From 50% to 74% 4: 4: From 75% to 100%	Ordinal
collection_percapita	Average daily amount of solid waste per capita	Values between .021 and 1.99 kg/inhabitant	Discreet

Source: own elaboration.

Also, Table 2 shows the management instruments that will be considered to estimate the Tobit model.

Table 2. Management instruments related to solid waste

	Variables	Variable type and values
PRS(Solid Waste Plan)	· Comprehensive Environmental Management Plan for Solid Waste · Solid Waste Management Plan · Solid Waste Transformation Program · Source Segregation and Selective Collection of Solid Waste Program · Solid Waste Collection System · Solid Organic Waste Recovery Plan · Solid Waste Characterization Study	Discrete from 0 to 6, where 0 indicates that the municipality does not have any PRS, 1: that it has at least one plan, etc.
Pdurbano	Urban Development Plan	0: No 1: Yes
Pei	Institutional strategic plan	0: No 1: Yes

Source: own elaboration

Table 3 shows the efficiency ranking of the 10 most efficient and least efficient municipalities.

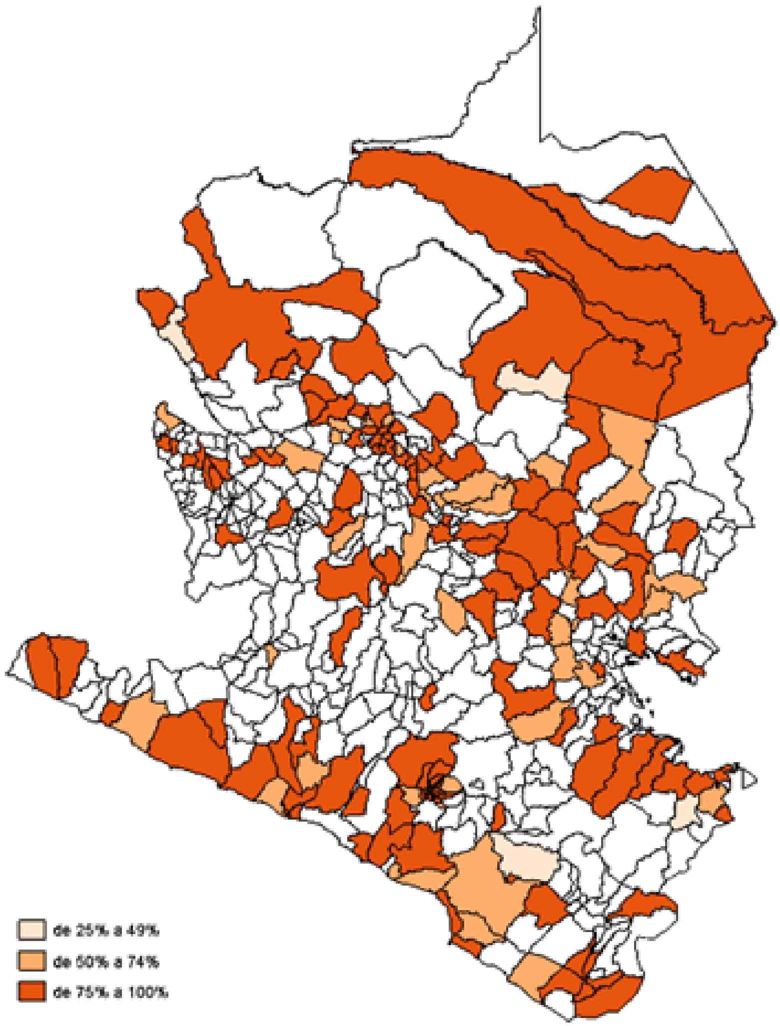
Table 3. **Efficiency results of district municipalities in solid waste collection per capita and coverage in solid waste collection.**

	DMU	Ranking	Theta		DMU	Ranking	Theta
Cusco	Machupicchu	1	1	Arequipa	Jacobo hunter	165	0.33
Cusco	Pichari	2	1	Puno	Coasa	166	0.28
Puno	Juli	3	1	Puno	Pucara	167	0.25
Madre de dios	Laberinto	4	1	Puno	Jose Domingo Choquehuanca	168	0.25
Madre de dios	Iberia	5	1	Moquegua	El algarrobal	169	0.25
Cusco	Chinchero	6	1	Madre de dios	Huepetuhe	170	0.25
Puno	Pichacani	7	1	Cusco	Coya	171	0.25
Cusco	Saylla	8	1	Puno	Potoni	172	0.21
Puno	Desaguadero	9	1	Puno	Cabanillas	173	0.18
Cusco	Ollantaytambo	10	1	Puno	Quilcapuncu	174	0.18

Source: Own elaboration using STATA 17.0

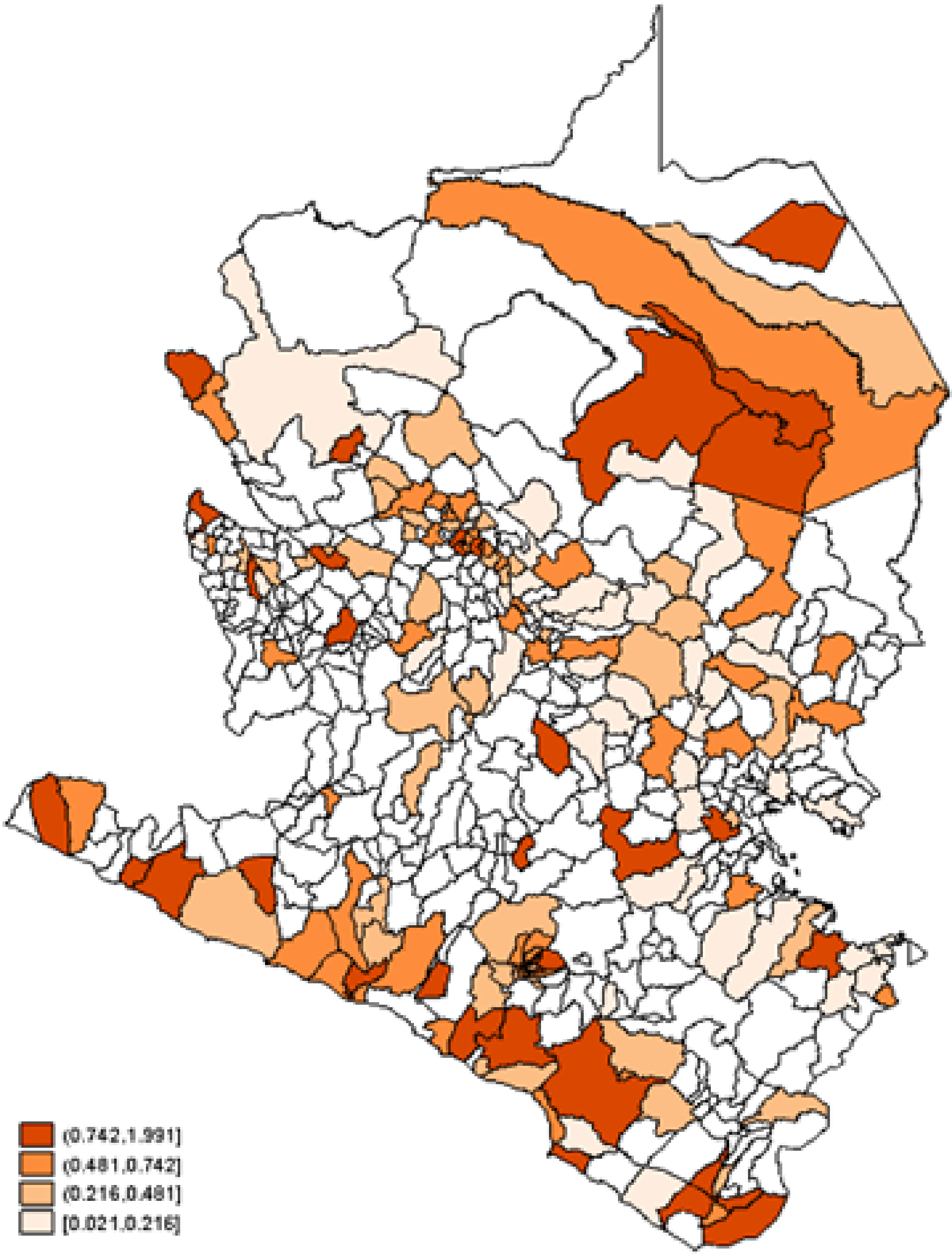
The results can also be observed through the following heat maps of the southern macro-region of Peru, which shows the municipalities and their respective coverage in Figure 1, as well as the amount of per capita solid waste collection in Figure 2.

Figure 1. Heat map of the percentage of solid waste collection coverage.



Source: Own elaboration using STATA 17.0

Figure 2. Heat map of the per capita amount of waste collection (kg/inhabitant)



Source: Own elaboration using STATA 17.0

According to the results obtained through the DEA analysis, using the inputs of waste collection trucks, number of cleaning personnel and collection frequency, five district municipalities were identified that appear to operate on the "frontier of efficiency". These municipalities have managed to optimize their resources for solid waste management, reflected in Theta values closer to 1. These municipalities are Machupicchu, Pichari, Juli, Laberinto and Iberia.

On the other hand, it was observed that some municipalities are at the opposite end of the ranking, with efficiency values close to zero. This suggests that these municipalities still have room to improve their solid waste management practices. These municipalities include Huepetuhe, Coya, Potoni, Cabanillas and Quilcapuncu.

In the case of the municipalities of Machupicchu and Pichari, the solid waste collection coverage is between 75% and 100% and the collection frequency is daily; in addition, both have a solid waste management plan, a solid organic waste recovery plan and a solid waste characterization study.

Likewise, the municipalities of Potoni, Cabanillas and Quilcapuncu, which are at the bottom of the efficiency ranking, have a waste collection coverage of between 50 and 74% and the collection frequency is once a week; the municipalities only have the solid waste management plan and lack other management instruments.

Finally, when comparing the municipalities at the extremes of relative efficiency, a particular case is observed between Pichari and Potoni. Both municipalities have two waste collection trucks; however, while Pichari manages to collect 35,000 kilos of solid waste, Potoni barely reaches 2,000 kilos. This contrast highlights how certain municipalities, despite having a similar amount of resources (inputs), manage to produce a considerably different output. The results of the Tobit model estimation are presented in Table 4.

Table 4. Results of the Tobit model

Variables	Marginals Effects
Solid Waste Plan (Prs)	0.0241* (0.0139)
Urban Development Plan (Pdurbano)	0.1465*** (0.0483)
Institutional strategic plan (Pei)	0.1127*** (0.0436)
F (3, 171)	14.52
pseudo R^2	0.4467
Prob > F	0
Log pseudolikelihood	-17.3088

Standard errors in parentheses, * p<.1, ** p<.05, *** p<0.01

Source: Own elaboration

According to the Tobit model results, the dependent variable is the level of efficiency and the independent variables are whether the municipalities have at least one solid waste plan, urban development plan and institutional strategic plan. The LR chi2(3) statistic yields a value of 27.95, which indicates that the considered variables are statistically significant jointly in explaining efficiency. Additionally, with a Prob > chi2 = 0.0000, the null hypothesis of coefficients equal to zero is rejected. In summary, these results suggest that the variables have a significant joint effect in explaining the efficiency evaluated.

5. Discussion

According to the DEA-Tobit model estimation, it was found that those municipalities that are in the top efficiency ranking have at least 3 solid waste plans; specifically, the municipalities of Machupicchu, Pichari and Juli. This contrasts with the municipalities that are in the last places of the ranking, such as Potoni, Cabanillas and Quilcapuncu, which only have 1 solid waste plan. In this sense, the importance of implementing strategic and logistical plans is highlighted, as suggested by Reyna et al. (2017) and Carvajal et al. (2022).

On the other hand, the mentioned municipalities have the same amount of inputs, such as cleaning personnel or collection trucks, given the importance of these, as Bernache (2015) points out; however Zhou et al. (2022) also highlights the importance of their training to improve the efficiency of their functions. This could be an indication of how some municipalities with the same amount of inputs achieve a much higher output by making more efficient use of resources. Especially considering that the variables were normalized in per capita terms.

Regarding the estimation of the Tobit model, its marginal effects allowed us to find that having an additional solid waste management plan is positively associated with the level of efficiency of the municipalities; on average, with an increase of 0.0241 units in efficiency with a significance level of 10%, keeping other variables constant.

Likewise, having an urban development plan has a positive relationship with efficiency in solid waste management. It is associated, on average, with an increase of 0.1465 units in efficiency at the 1% significance level, compared to municipalities that do not have such a plan, holding other variables constant. These results are in line with those found by García-Mondragón et al. (2023), who considers that when implementing these management instruments, they act as a theoretical guide for the solid waste management process, but it is crucial to consider the evolution and production of solid waste that could exceed the action capacity of the plans.

In addition, the existence of an institutional strategic plan is linked, on average, to an increase of 0.1127 units in efficiency at the 1% significance level, compared to municipalities that lack an institutional strategic plan, holding other variables constant.

Consequently, public policies and strategic plans should focus on promoting environmental education and stimulating active citizen participation in environmental preservation. This approach can trigger a series of valuable and significant benefits and opportunities, such as a reduction in the production of solid waste, the extension of the useful life of disposal sites, the strengthening of a formal recycling market, the creation of new businesses to meet the needs of the sector, and the generation of both direct and indirect employment. Likewise, within the framework of state reform and modernization, strategic planning has acquired significant importance and is considered fundamental to achieving organizational objectives more efficiently and effectively (Castro, 2014).

6. Conclusions

The results of the analysis show that some municipalities operate with high efficiency in solid waste management, while others have room for improvement. For example, it was observed that municipalities such as Pichari manage to collect a considerable amount of solid waste with resources similar to those that collect a much smaller amount, such as Potoni. It was identified that the most efficient municipalities usually have several solid waste management plans. Additionally, it was found that the presence of urban development and institutional strategic plans is positively related to efficiency. These results highlight the importance of strategic planning and efficient resource use in solid waste management. However, it is also acknowledged that the action capacity of the plans can be exceeded by the evolution of waste production, which suggests the need for adaptability in these management strategies.

As a future research line, it is proposed to carry out a comparative analysis at the national and international levels with the aim of identifying the best practices in solid waste management. This study will not only allow the recognition of successful strategies in different contexts, but will also provide the opportunity to explore innovations and avant-garde approaches in the field; in addition, it will offer valuable knowledge for the adaptation and improvement of existing policies and practices in the district municipalities of the southern macro-region of Peru, thus promoting more effective and sustainable management of urban solid waste.

7. Author Contributions

Ernesto Carlos Narciso Quispe Huayta: Conceptualization, Investigation, Formal analysis, Writing – original draft, Methodology, Supervision, Validation, Visualization, Writing – review & editing. Edson Efrain Sarmiento Quispe: Conceptualization, Investigation, Formal analysis, Writing – original draft, Methodology, Supervision, Validation, Visualization, Writing – review & editing. Lisbeth Whitney Calli Vilca: Conceptualization, Investigation, Formal analysis, Writing – original draft.

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